

Review

Origin of magmas in subduction zones: a review of experimental studies

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(Contributed by Ikuo KUSHIRO, M.J.A.)

Abstract: Studies of the origin of magmas in subduction zones, particularly in the Japanese island arc, have been significantly advanced by petrological, geochemical, geophysical and experimental studies during last 50 years. Kuno's original model¹⁾ for magma generation in the Japanese island arc, that tholeiite magmas are formed at relatively shallow levels in the mantle on the Pacific Ocean side whereas alkali basalt magmas are formed in deeper levels on the Japan Sea side, stimulated subsequent studies, particularly high-pressure experimental studies in which the author participated. Recent seismic tomographic studies of regions beneath the Japanese island arc demonstrate that seismic low-velocity zones where primary magmas are formed have finger-like shapes and rise obliquely from the Japan Sea side toward the Pacific Ocean side. Based on experimental studies, it is suggested that the compositions of primary magmas depend mainly on the H₂O content and degree of melting in the melting zones, and that primary tholeiite magmas are formed by 10–25% melting of the source mantle containing less than 0.2 wt.% H₂O. High-alumina basalt and alkali basalt magmas are formed by smaller degrees of melting of similar mantle, whereas primary boninite magmas are formed by more than 20% melting of the source mantle with more than 0.2 wt.% H₂O, and finally, high-magnesia andesite magmas are formed by smaller degrees of melting of similar mantle.

Keywords: subduction zone, magma, melting relation, mantle peridotite, degree of melting, H₂O content

Introduction

The origin of volcanic rocks and their primary magmas in subduction zones, including island arcs, is an important problem in igneous petrology. Studies of volcanic rocks in the Japanese island arc began in the late 19th century and greatly advanced during the early-middle 20th century, based mainly on the petrological characters of volcanic rocks.^{2)–8)} Tomita⁵⁾ recognized the occurrence of relatively silica-poor, alkali-rich rocks along the coast of the Japan Sea region and proposed the “Circum-Japan Sea alkaline province”. Later, Kuno¹⁾ clarified the lateral variations of volcanic rocks, particularly basalts, along the entire Japanese island arc. He found that relatively silica-rich, alkali-poor tholeiitic basalts (tholeiite) occur along the Pacific Ocean side

(including the Izu islands), whereas those of relatively silica-poor alkali basalts occur on the Japan Sea side. These lateral variations of basalts were also observed in other parts of the circum-Pacific volcanic belt, including continental margins, such as along the western margins of both the north and south American continents. In these areas, tholeiitic basalts occur on the Pacific Ocean side and alkali basalts occur on the continental side. Furthermore, Kuno discussed the origin of such lateral variations based on his earlier work on the Hawaiian basalts⁸⁾; tholeiitic basalt magmas are generated at relatively shallow levels in the mantle and alkali basalt magmas at deeper levels by partial melting of mantle peridotite. Kuno¹⁾ also took into account the seismic studies in the Japanese island arc. He realized that the boundary between the zones of tholeiitic basalt and alkali basalt nearly coincides with the 200 km depth

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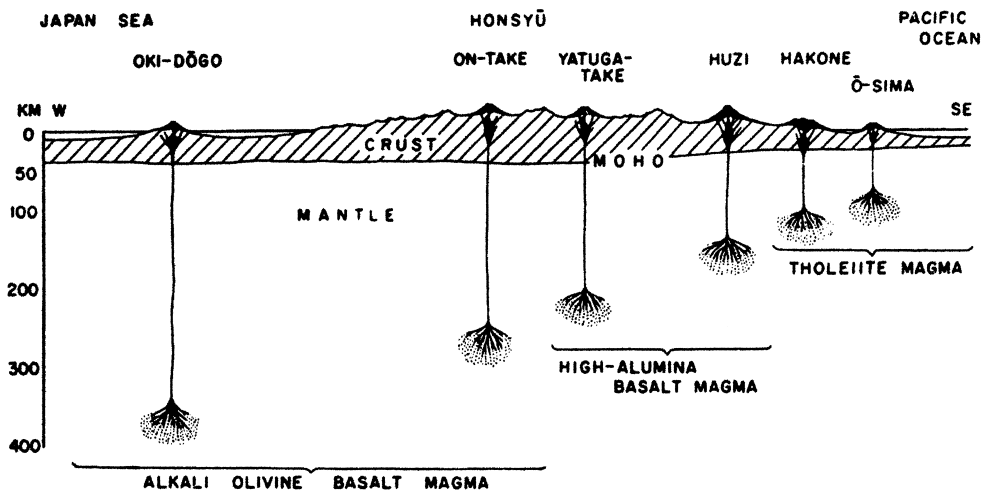


Fig. 1. Kuno's model for the generation of tholeiite, high-alumina basalt and alkali olivine basalt magmas in the Japanese island arc.^{1), 10)}

contour of the deep seismic zone found by Wadati and Imai.⁹⁾ Kuno¹⁾ proposed, based on this evidence, that tholeiitic basalt magmas are formed at depths shallower than about 200 km and alkali basalt magmas at depths greater than 200 km. Later, Kuno¹⁰⁾ recognized the zone of high-alumina basalt between those of tholeiitic basalt and alkali basalt and suggested that high-alumina basalt magmas are generated at depths near 200 km (Fig. 1). Kuno's studies greatly stimulated subsequent studies, particularly high-pressure experimental studies. In early 1960s the author was also stimulated by Kuno's work and participated in the studies of magma genesis in island arcs by conducting high-pressure experiments. In this brief article, studies on the origin of subduction zone magmas are briefly reviewed, with special reference to the author's relevant experimental studies. Possible physical conditions of magma generation in the mantle beneath the Japanese island arc are also discussed.

High-pressure experimental studies on the genesis of subduction zones magmas

From the beginning of 1960s, high-pressure experimental studies on the origin of basalt magmas started intensively, partly due to the development of the piston-cylinder high-pressure apparatus¹¹⁾ and partly because of the vigorous debates on genetic relationships between tholeiite and alkali basalt magmas, including the above-mentioned model of Kuno.¹⁾ The most noteworthy study was

made by Yoder and Tilley,¹²⁾ who conducted a series of experiments on basaltic compositions at 1 atmosphere and at high pressures. These workers showed that tholeiite-type magma is formed at relatively low pressures or at shallow depths in the mantle and alkali basalt-type magma at higher pressures or at greater depths from the same primary source rock in the mantle. Their discussion is consistent with Kuno's model; however, the proposed mechanisms of generation of two basalt magmas were different (i.e., direct partial melting of source mantle peridotite vs. fractional crystallization of a more primitive magma). In order to examine the Kuno's model, Kushiro^{13), 14)} conducted high-pressure experiments in the systems $\text{Mg}_2\text{SiO}_4\text{-NaAlSiO}_4\text{-SiO}_2$, $\text{Mg}_2\text{SiO}_4\text{-CaMgSi}_2\text{O}_6\text{-SiO}_2$ and $\text{Mg}_2\text{SiO}_4\text{-CaAl}_2\text{SiO}_6\text{-SiO}_2$ which include the major components of mantle peridotites. Fig. 2 shows the shift of the forsterite-enstatite liquidus boundary with pressure in the system $\text{Mg}_2\text{SiO}_4\text{-NaAlSiO}_4\text{-SiO}_2$. As shown in the figure, melts in equilibrium with forsterite and enstatite, which lie on the forsterite-enstatite liquidus boundary, become more silica-depleted and Na-enriched with increasing pressure. At 2.0 and 3.0 GPa, the low-temperature parts (upper parts) of the liquidus boundaries lie in the nepheline normative compositional area ($\text{Mg}_2\text{SiO}_4\text{-NaAlSi}_3\text{O}_8\text{-NaAlSiO}_4$ triangular area). The results imply that magmas formed by partial melting of mantle peridotite have relatively silica-rich tholeiitic compositions at low pressures, whereas they have

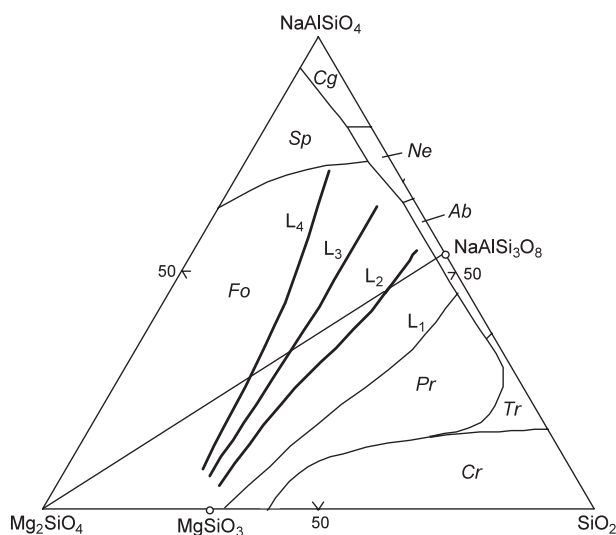


Fig. 2. Liquidus diagram of the system forsterite (Mg_2SiO_4)-nepheline ($\text{NaAlSi}_3\text{O}_8$)-silica. Thin curves are liquidus boundaries at 1 atm (Fo, forsterite; Pr, protoenstatite; Cr, cristobalite; Tr, tridymite; Ab, albite; Ne, nepheline; Cg, carnegieite; Sp, spinel). L_1 : forsterite-protoenstatite liquidus boundary at 1 atm; Thick curves L_2 , L_3 and L_4 : forsterite-enstatite liquidus boundary at 1.0, 2.0 and 3.0 GPa, respectively.^{13), 14)}

silica-poor alkali basaltic compositions at high pressures, thus supporting Kuno's model. However, the pressure ranges where two magmas are formed are much lower than those in Kuno's model. The results of Kushiro's experiments indicate that even alkali basaltic magmas can be formed at pressures less than 2.0 GPa (depths < 60 km), compared to > 200 km in the Kuno's model. Green and Ringwood¹⁵⁾ and Green *et al.*¹⁶⁾ also discussed, based on their high-pressure experiments on natural basalt compositions, that the depth ranges for generation of silica-saturated tholeiite, high-alumina basalt, and alkali basalt magmas are < 15 km, 15–35 km, and 35–60 km, respectively. These depth ranges are much shallower than those in Kuno's model; however, they suggested that the deep earthquake foci may be related to the initiation of upward movement of mantle materials, which eventually partially melt at shallower depths and finally undergo magma segregation.

The depth ranges where tholeiite, high-alumina basalt and alkali basalt magmas originate were estimated using primitive magma compositions of these three basalts in the Japanese island arc. Tatsumi *et al.*¹⁷⁾ obtained the primitive basalt magma compositions, which are in equilibrium with mantle peridotite, by taking an inverse process of fractional crys-

tallization of olivine (maximum olivine fractionation model). These workers then performed high-pressure experiments to find the pressure-temperature conditions where melts of those primitive basalt compositions are in equilibrium with the major minerals of mantle peridotite, i.e., olivine and orthopyroxene. Their results demonstrate that primitive tholeiite, high-alumina basalt, and alkali basalt melts are in equilibrium with mantle peridotite (Iherzolite or harzburgite) at 1.1 GPa–1320 °C, 1.5 GPa–1340 °C and 1.7 GPa–1360 °C, respectively under anhydrous conditions. The pressure-temperature conditions where melts of primitive high-alumina basalt and alkali basalt compositions are equilibrated with mantle peridotite in the presence of small amounts of H_2O were also determined; they are 1.7 GPa–1325 °C and 2.3 GPa–1320 °C in the presence of 1.5 and 3.0 wt.% H_2O , respectively. The effect of H_2O on the composition of magma and temperature of its generation is discussed in more detail below. The results of Tatsumi *et al.*¹⁷⁾ indicate that tholeiite, high-alumina basalt and alkali basalt magmas originate at depths 35 km, 45–50 km and 50–70 km in the Japanese island arc. Another important finding of their study is that the temperatures of generation of these magmas are considerably high; they are higher than 1300 °C at depths of 35 km, even in the presence of small amounts of H_2O . These results have provided important constraints on the thermal structures and dynamics of the mantle beneath the Japanese island arc, and other arcs as well.

Effect of H_2O on the generation of subduction zone magmas

Magmas formed in subduction zones contain significant amounts of H_2O , as inferred from the occurrence of hydrous minerals and the composition of glasses in the products of volcanic eruptions. Recently many glass inclusions in minerals, particularly those contained in magnesian olivine in primitive volcanic rocks in subduction zones, have been found to contain significant amounts of H_2O . The compositions of such melt inclusions are close to those of primary magmas. The most significant effect of H_2O is to lower melting temperatures of minerals and rocks, as demonstrated in several pioneering experimental studies.^{18)–20)} Another important effect is to change the compositions of melts in equilibrium with minerals.^{20)–22)} The effects of H_2O on the generation of magmas in peridotitic mantle have been

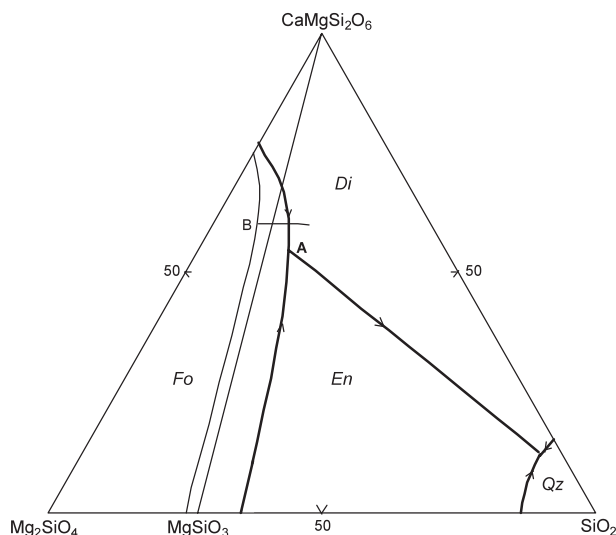


Fig. 3. Liquidus diagram of the system forsterite (Mg_2SiO_4)-diopside ($\text{CaMgSi}_2\text{O}_6$)-silica at 2.0 GPa under hydrous and anhydrous conditions.²⁹⁾ Thick and thin curves indicate liquidus boundaries under hydrous (H_2O -saturated) and anhydrous conditions, respectively. A and B are isobaric invariant points where melt coexists with forsterite, enstatite and diopside. Fo, forsterite; Di, diopside; En, enstatite; Qz, quartz.

studied since the late 1960s. The effect of H_2O on the temperature of melting of mantle peridotites was determined by Kushiro *et al.*,²³⁾ Green²⁴⁾ and Mysen and Boettcher.²⁵⁾ The solidus of a mantle peridotite (lherzolite) from Salt Lake crater, Hawaii determined by Kushiro *et al.*,²³⁾ is at about 1000°C at pressures between 1.0 and 4.0 GPa under hydrous (H_2O -saturated) conditions compared to 1300 – 1600°C under anhydrous conditions as shown below. Green²⁴⁾ determined the solidus of a mantle peridotite composition (pyrolite) containing different amounts of H_2O and showed that the solidus is about 1000°C under H_2O -saturated conditions and 1100 – 1170°C under H_2O -undersaturated conditions (with 0.2 wt.% H_2O) at pressures between 1.0 and 3.0 GPa.

Concerning the compositions of magmas formed by partial melting of mantle peridotite under hydrous conditions, O'Hara²⁷⁾ first suggested that, under hydrous conditions, such magmas are silica-oversaturated rather than silica-undersaturated. Kushiro *et al.*²⁸⁾ and Kushiro²⁹⁾ demonstrated experimentally that H_2O has an effect of increasing the silica content of magmas formed by partial melting of mantle peridotite. Fig. 3 shows the effect of H_2O on the compositions of melts in the system Mg_2SiO_4 - $\text{CaMgSi}_2\text{O}_6$ - SiO_2 at 2.0 GPa.²⁹⁾ Points A

and B are isobaric invariant points, where melts are in equilibrium with three major minerals of mantle peridotite, namely forsterite, enstatite and diopside, under H_2O -saturated and anhydrous conditions, respectively. Isobaric invariant point B is located on the forsterite side of the join MgSiO_3 - $\text{CaMgSi}_2\text{O}_6$ and is silica-undersaturated, whereas A is on the silica-side of the join and is silica-oversaturated because of the expansion of the liquidus field of forsterite relative to that of enstatite. This means that silica-oversaturated magmas, such as tholeiite, can be formed by partial melting of mantle peridotite consisting of magnesian olivine, orthopyroxene and clinopyroxene at 2.0 GPa (or at depths of 60 km) under H_2O -saturated conditions. It is unlikely, if not impossible, that H_2O -saturated conditions commonly occur in the upper mantle as discussed below; however, the effect of H_2O must be taken into consideration in the formation of magmas in subduction zones. Kushiro and Sato³⁰⁾ and Tatsumi³¹⁾ conducted hydrous melting experiments on high-magnesia andesites (SiO_2 , 56.75 and 59.44 wt.%; MgO, 9.16 and 9.62%, respectively) from the Setouchi volcanic belt, southwest Japan and demonstrated that the magmas of these high-magnesia andesites can be formed at pressures lower than 1.7 and 1.5 GPa, respectively by partial melting of hydrous mantle peridotite. Silica-saturated tholeiite was also examined under hydrous conditions by Nichols and Ringwood,³²⁾ and was found to coexist with mantle peridotite at pressures less than 2.0 GPa (<60 km). Boninite, a high-magnesia, high-silica volcanic rock, was also examined by Umino and Kushiro.³³⁾ They found that a boninite from Chichi-jima (SiO_2 , 57.96, MgO, 11.93 wt.%) can coexist with mantle peridotite at pressures up to 1.7 GPa (about 50 km depth) under H_2O -saturated hydrous conditions. These experimental results, together with those of the subsequent experiments,^{34)–36)} indicate that H_2O increases the depth range in which tholeiite and other relatively silica-enriched magmas can be formed by partial melting of mantle peridotite. Silica-saturated tholeiite and silica-undersaturated olivine tholeiite magmas can be formed at depths down to 60 and 100 km, respectively. This is significantly deeper than those under anhydrous conditions, and high-magnesia andesite and boninite magmas can be formed at depths to about 50 km in the presence of H_2O .

Subduction-zone magmas contain significant

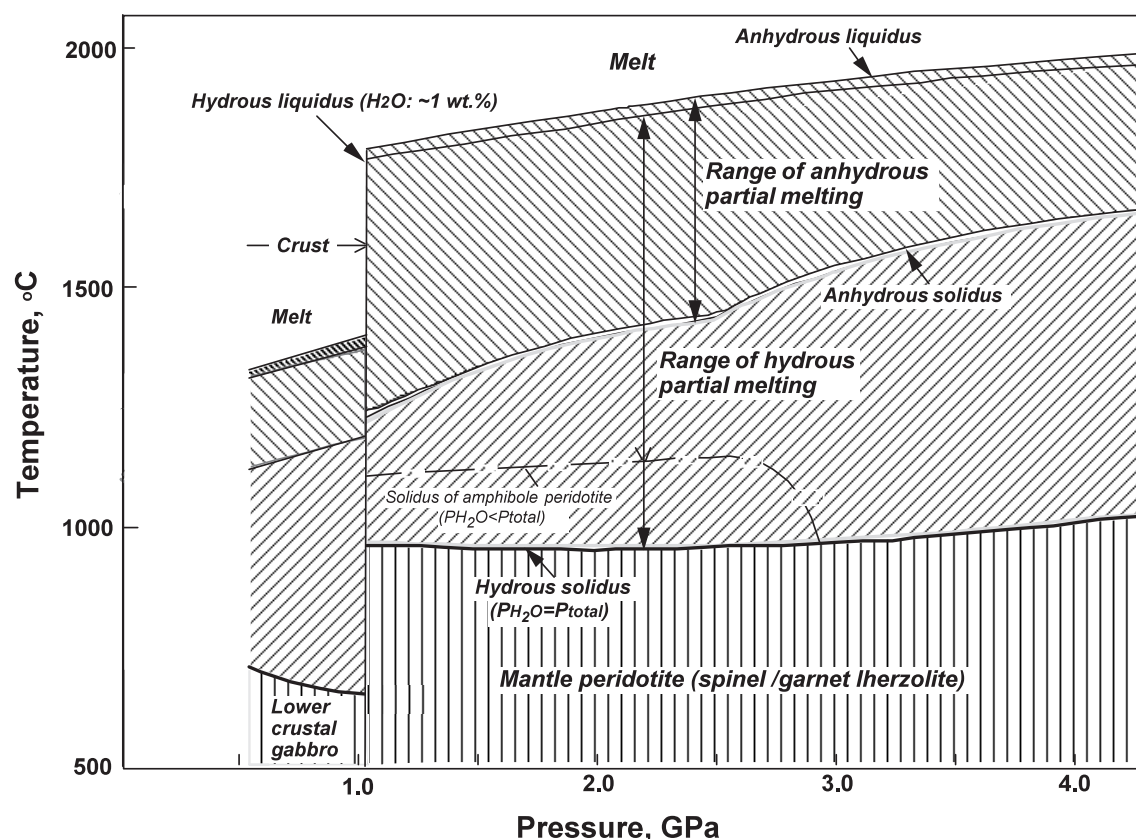


Fig. 4. Liquidi and solidi of mantle peridotite (spinel or garnet lherzolite) under both hydrous and anhydrous conditions.^{23), 24), 26)} $P_{H_2O}=P_{total}$ is H_2O -saturated condition. Those at pressures between 0.5 and 1.0 GPa are for gabbro of the lower crust.¹²⁾

amounts of H_2O ; however, most of these are not saturated with H_2O when formed in the mantle. Studies of melt inclusions in olivine in volcanic rocks in subduction zones indicate that the melt inclusions in some primitive volcanic rocks with high MgO and $Mg\#(Mg/(Mg+Fe))$ contain 1.2–3.0 wt.% H_2O .³⁷⁾ Such amounts of H_2O are much lower than those for H_2O saturation; however, they affect significantly temperature and composition of magmas formed by partial melting of mantle peridotite. Kushiro³⁸⁾ conducted melting experiments on a mantle peridotite at 1.2 GPa under H_2O undersaturated conditions using the ‘sandwich method’. The results show that the compositions of melts are olivine tholeiitic even in the presence of 5.0 and 6.6 wt.% H_2O at 1200 °C, but they are more silica-rich than most olivine tholeiites with similar Fe/Mg ratios. At 1150 °C, the composition of a melt containing 4.4 wt.% H_2O is high-alumina basaltic and melts containing 8 wt.% H_2O or more are silica-oversaturated and boninitic.

Hirose and Kawamoto³⁹⁾ and Hirose⁴⁰⁾ conducted experiments on the melting of lherzolite KLB1 at 1.0 GPa and showed that melts are also basaltic (SiO_2 , 50~53 wt.%) with lower H_2O contents and become more silica-rich and high-magnesia andesitic at higher H_2O contents. Gaetani and Grove⁴¹⁾ conducted detailed experiments to determine compositions of melts in equilibrium with lherzolite mineral assemblages at 1.2–2.0 GPa with H_2O up to 12 wt.% in the melts. They showed that both SiO_2 activity and SiO_2 content (anhydrous base) of melts increase with greater amounts of dissolved H_2O . However, the increase in the SiO_2 content in partial melts is significantly less than would be necessary to produce andesitic magmas from partial melting of hydrous mantle peridotite.

Melting phase relations of mantle peridotite under H_2O -undersaturated conditions

To understand the changes in composition

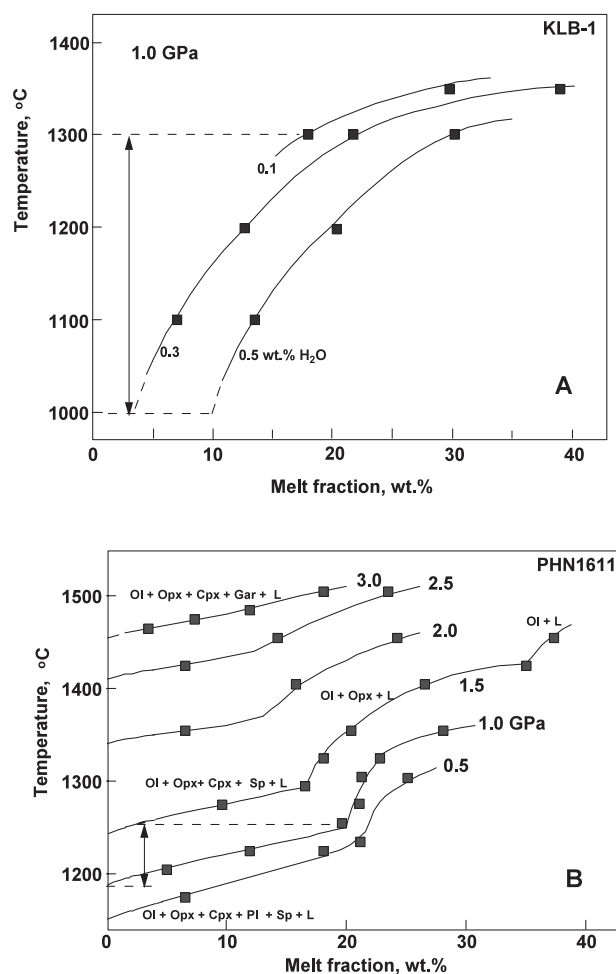


Fig. 5. Changes of melt fraction (degree of melting) with temperature under hydrous and anhydrous conditions. A: Mantle peridotite KLB1 at 1.0 GPa under hydrous conditions³⁹⁾; B: Mantle peridotite PHN1611 at 0.5–3.0 GPa under anhydrous conditions.⁴²⁾ Arrows in A and B indicate the temperature ranges for 20% melting at 1.0 GPa.

and H₂O content of magmas formed under H₂O-undersaturated conditions, melting phase-relations of mantle peridotite under hydrous conditions between the two extreme cases, H₂O-saturated and anhydrous conditions, are examined. Fig. 4 shows the liquidi and solidi of mantle peridotite under both anhydrous and H₂O-saturated conditions. The shaded area between the solidus under H₂O-saturated conditions ($P_{H_2O}=P_{total}$) and the liquidus under anhydrous conditions marks the melting temperature range where H₂O-undersaturated magmas with variable H₂O contents are formed. In this range, the H₂O content of magma decreases and the degree of melting increases with increasing temperature at

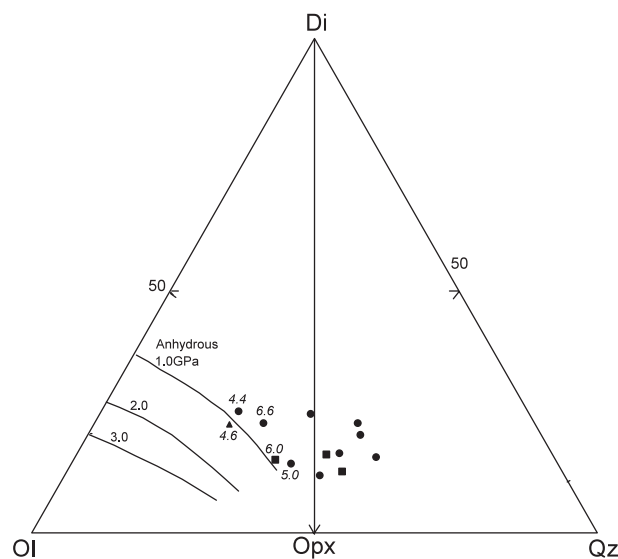


Fig. 6. Compositions of melts formed by partial melting of mantle peridotite (spinel lherzolite) HK66 under hydrous conditions plotted on the pseudo-ternary diagram Ol (olivine)-Di (diopside)-Qz (silica).³⁸⁾ Opx, orthopyroxene. Solid circles, squares and triangle are melts formed at 1.2, 1.6 and 2.0 GPa, respectively. Italic numbers are H₂O contents (wt.%) in the melts. Melts with no numbers contain >10 wt.% H₂O. Thin curves indicate compositional trends of melts formed by partial melting of the same peridotite at 1.0, 2.0, and 3.0 GPa under anhydrous conditions.⁵¹⁾

constant pressure. Fig. 5A shows the changes of degree of melting (melt fraction) of mantle peridotite KLB1 as function of temperature at 1.0 GPa under hydrous conditions by Hirose and Kawamoto³⁹⁾ and Fig. 5B shows that of mantle peridotite PHN1611 at pressures between 0.5 and 3.0 GPa under anhydrous conditions by Kushiro.⁴²⁾ It is shown that the temperature range for 20% melting of mantle peridotite at 1.0 GPa is much wider under hydrous conditions than under anhydrous conditions (300° and 70°, respectively). The experiments of Gaetani and Grove⁴¹⁾ on a different mantle peridotite at 1.5 GPa under hydrous conditions also show a wide temperature range (i.e. >200° for 20% melting). In the wide melting temperature range between the H₂O-saturated solidus and the anhydrous liquidus in Fig. 4, the composition of melt changes significantly. Contrarily, under anhydrous conditions, the melting temperature range is smaller and the compositional change of melt is relatively small. Such a large difference in melting temperature range is the fundamental difference between hydrous conditions such as island arcs or subduction zones and nearly anhydrous conditions

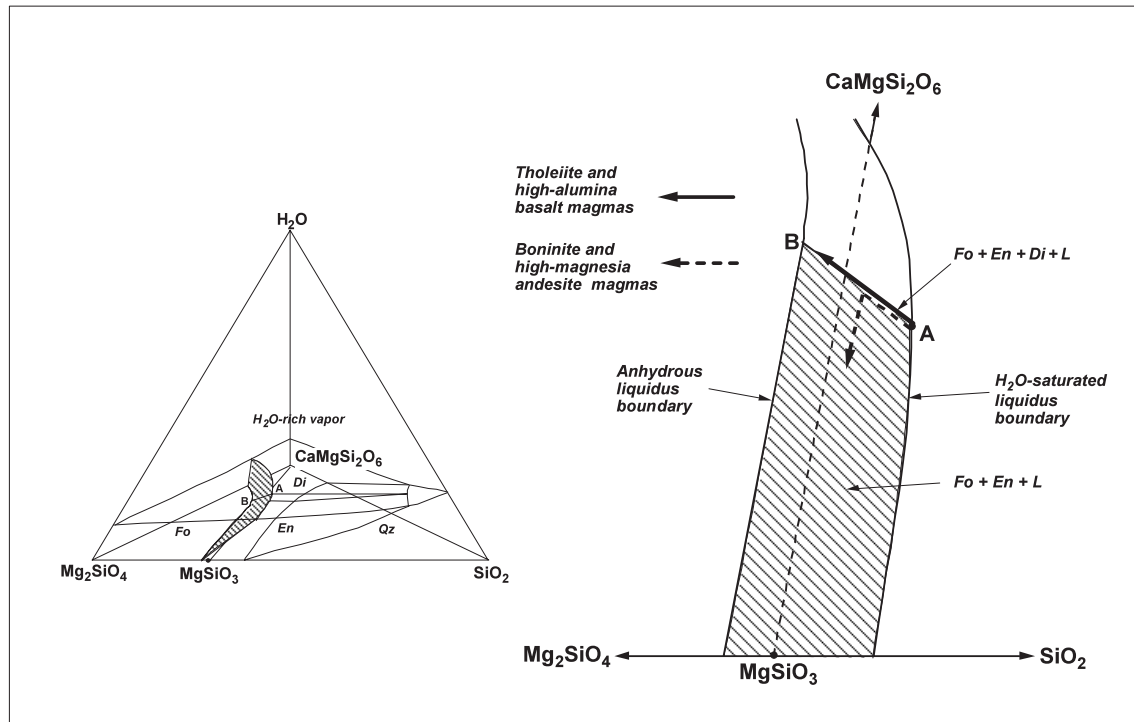


Fig. 7. The system Mg_2SiO_4 - $\text{CaMgSi}_2\text{O}_6$ - SiO_2 - H_2O at 2.0 GPa.^{29), 43)} The right-hand figure is the shaded plane of the left-hand figure projected from the H_2O apex. Abbreviations as in Fig. 3.

such as mid-oceanic ridges. The SiO_2 contents of melts increase with increasing H_2O content at constant pressure in the experiments³⁸⁾⁻⁴⁰⁾; however the absolute SiO_2 contents of melts are different due to the difference in the composition of the starting materials. Fig. 6 shows the compositions of melts in equilibrium with mantle peridotite under both H_2O -undersaturated, hydrous conditions and anhydrous conditions in the pseudo-ternary system olivine(Ol)-diopside (Di)- SiO_2 (Qz). As shown in the figure, the Qz/Ol ratio or SiO_2/MgO ratio of melts are significantly large in the hydrous melts at pressures between 1.2–2.0 GPa and the melts with high H_2O contents are silica-oversaturated (plotted in the Opx-Di-Qz area) even at 1.6 GPa. Under anhydrous conditions, melts remain silica-undersaturated at pressures higher than 1.0 GPa.

These compositional changes of melts can be explained by the phase equilibrium relations in the system Mg_2SiO_4 - $\text{CaMgSi}_2\text{O}_6$ - SiO_2 - H_2O at 2.0 GPa as established by Kushiro^{29), 43)} (Fig. 7). Points A and B are isobaric invariant points where melts are in equilibrium with major mineral components of mantle peridotite (i.e. forsterite, diopside and enstatite)

under H_2O -saturated and anhydrous conditions, respectively. Point A is silica-oversaturated whereas point B is silica-undersaturated as noted in Fig. 3. The shaded area shows a plane where melts are H_2O -undersaturated and coexist with forsterite and enstatite or diopside. The right-hand figure shows the same plane projected from the H_2O apex onto the Mg_2SiO_4 - $\text{CaMgSi}_2\text{O}_6$ - SiO_2 plane. When melting of mantle peridotite occurs in the presence of relatively small amounts of H_2O , the first melt produced is A, which is silica-oversaturated and also H_2O -saturated. As melting progresses, the composition of melt leaves A and changes along the univariant curve A-B in the H_2O -undersaturated region and becomes less silicic. At a certain point on the univariant curve A-B, diopside disappears and melt leaves the curve A-B and changes toward MgSiO_3 on the shaded plane. The point where the melt leaves the curve A-B depends on the initial H_2O content — the larger the initial H_2O content, the closer this is to A. Melts are, therefore, more silica-rich and even silica-oversaturated through the melting range, when the initial H_2O contents are relatively large. This is shown by a dashed arrow in the right-hand figure,

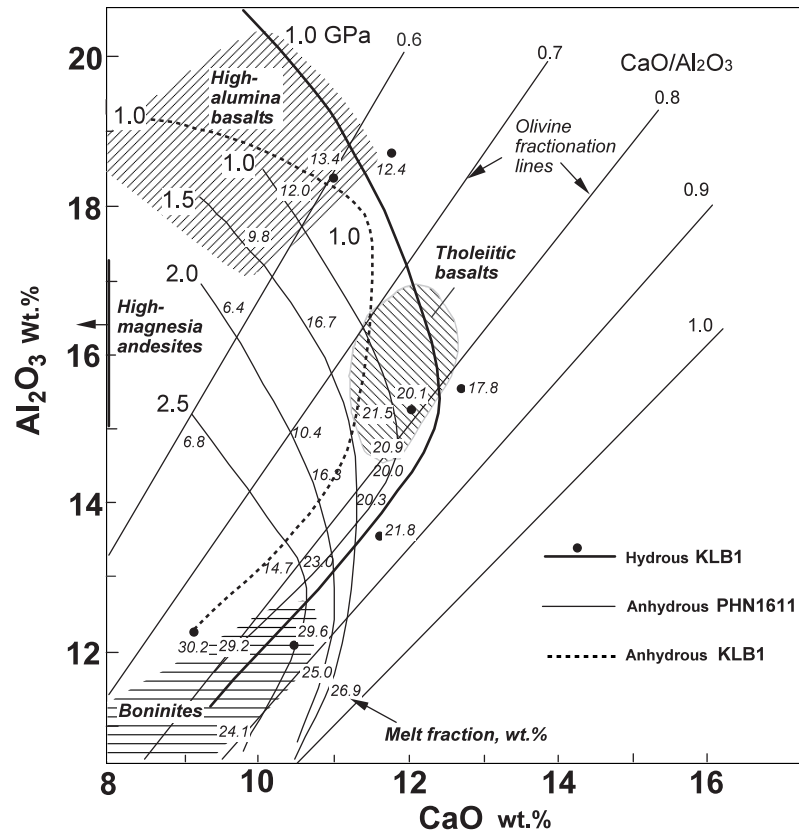


Fig. 8. CaO and Al_2O_3 contents of partial melts of mantle peridotites and those of volcanic rocks from island arcs having relatively high Mg/Fe. Italic numbers denote degree of melting of mantle peridotite in wt.%. Thick curve with solid circles indicates the compositional trend of partial melts formed from mantle peridotite KLB1 under hydrous conditions,³⁹⁾ and dashed and thin curves indicate respectively those formed from mantle peridotites KLB1 and PHN1611 under anhydrous conditions.^{42), 50)} Thin straight lines indicate constant $\text{CaO}/\text{Al}_2\text{O}_3$ ratios.

whereas they cross the join $\text{CaMgSi}_2\text{O}_6$ - MgSiO_3 and become silica-undersaturated as shown by a thick arrow when the initial H_2O contents are relatively small. The former case would correspond to the generation of high-magnesia andesite and boninite magmas, and the latter case would correspond to high-alumina basalt and some island arc tholeiite magmas.

Degree of melting and H_2O content of subduction zone magmas

The degree of melting for primary magmas formed in the mantle has been estimated in many geochemical studies, particularly those based on trace element data from volcanic rocks.^{44)–49)} Here, the degree of melting for subduction zone magmas is estimated based on the partial melting experiments on mantle peridotites. Fig. 8 shows the Al_2O_3 and CaO contents of partial melts formed from two

different mantle peridotites.^{39), 42), 50)} The numbers in italics indicate the degrees of melting in wt.%. As shown in the figure, the Al_2O_3 contents of partial melts decrease with increasing degree of melting for mantle peridotites. Fig. 8 also shows the compositional ranges of representative island arc volcanic rocks having relatively high Mg/Fe, namely tholeiites, high-alumina basalts, high-magnesia andesites and boninites. Most of these compositions do not represent those of the primary magmas but would have changed during their ascent, mainly by olivine fractionation. The compositional changes of magmas by olivine fractionation follow the constant $\text{CaO}/\text{Al}_2\text{O}_3$ lines in Fig. 8. The compositions of primary magmas of these volcanic rocks are, therefore, more or less shifted toward lower Al_2O_3 and CaO contents regions. Taking the olivine fractionation effect into account, the degrees of melting are relatively small for high-alumina basalts and high-magnesia

andesites, relatively large for tholeiites, and largest for boninites. The absolute values of degree of melting depend on unknown factors such as the composition of mantle peridotite, the pressure at the site of magma generation and the extent of olivine fractionation, so that they cannot be estimated exactly. On the assumption that the source mantle is close to the mantle peridotite KLB1 and PHN1611 (CaO, 3.26 and 3.44 wt.%; Al_2O_3 , 2.70 and 3.59 wt.%, respectively), the degrees of melting are estimated approximately to be less than 15 wt.% for high-alumina basalt and high-magnesia andesite magmas, 10–25% for tholeiite magmas and >20% for boninite magmas.

The H_2O contents of subduction-zone magmas are estimated from the H_2O contents in primitive basalt glasses quenched under deep sea conditions and those in melt inclusions in olivine in magnesian island arc volcanic rocks. The H_2O contents in primitive Mariana trough glasses measured by Stolper and Newman⁵²⁾ range from 0.5 to 1.9 wt.%, and those of melt inclusions in olivine phenocrysts in island arc tholeiites and boninites obtained by Sobolev and Chaussidon³⁷⁾ are 1.3–2.5 wt.% and 1.2–2.9 wt.%, respectively. The boninites studied by them are magnesian and primitive (most of them have $\text{Mg\#} > 75$), and therefore, the H_2O contents are considered to be close to those in primary island arc magmas. The tholeiites are, however, less magnesian (Mg\# 64.7–72.4) and more or less fractionated, and the H_2O contents in primary island arc tholeiite magmas would be less than those shown above. The H_2O content for most magnesian tholeiite (Mg\# 72.4) is 1.3 wt.%, and this value may be close to the representative value for primary island arc tholeiite magmas.

Fig. 9 shows the melt fraction (degree of melting) and H_2O contents for subduction zone magmas based mainly on the above estimates and assumptions and partly on the experimental data.³⁹⁾ The H_2O contents in high-alumina basalt and alkali basalt magmas have not been measured but they are suggested to be larger than those of tholeiites.^{17), 53)} The H_2O contents of primary high-magnesia andesite magmas are also not known, but they are considered to be close to or even higher than those of boninite magmas based on the experimental results.^{33), 38)–40)} The curves in Fig. 9 show the relation between the degree of melting and the H_2O contents of magmas formed by partial melting of mantle peridotite with differing initial H_2O content. Tholeiite and high-alumina basalt magmas lie along or slightly below

the curve for 0.2 wt.% H_2O (i.e., between the curves for 0.1 and 0.2 wt.%), whereas boninite magmas lie near the curve for 0.5 wt.% H_2O and high-magnesia andesite magmas probably between 0.5 and 0.2 wt.%. These estimates will likely change as more reliable data on the compositions of source mantle and the H_2O contents and degrees of melting for primary island arc magmas become available. However, the relative relations shown here will not change drastically. The implication of this figure is that the H_2O content of island arc mantle should be different for generation of different magmas; that is, the mantle that generates boninite and high-magnesia andesite magmas should have higher H_2O contents than the mantle that generates tholeiite, high-alumina basalt and alkali basalt magmas.

The H_2O content and temperature in the source mantle could be variable within a narrow space (e.g., within a single diapir⁵⁴⁾) and the compositions and H_2O contents of magmas formed in such a narrow region could change significantly. Also, the H_2O content and temperature in the same part of the mantle could change with time. In such cases, different magmas having different H_2O contents (e.g., tholeiite and boninite magmas) could erupt within the same, or within closely spaced areas of Earth's surface.

Conditions of magma generation beneath the Japanese island arc based on seismic tomography

Recently, significant progress has been made in understanding the physical properties of the mantle wedge beneath the Japanese island arc based on 3-dimensional seismic tomography. Fig. 10 reproduces P-wave velocity perturbations in northeast Honshu as determined by Nakajima *et al.*,⁵⁵⁾ who made seismic wave observations at 230 stations. As shown in the figure, the low-velocity region for P waves extends from deeper levels on the Japan Sea side to shallower levels on the Pacific Ocean side where many active volcanoes exist. The negative perturbation in most parts of the low velocity regions beneath northeast Honshu ranges from 3 to 6%. The S-wave velocities are also small in these regions. Velocities of P and S waves generally decrease with increasing temperature. In particular, S-wave velocities drastically decrease as melting begins to occur. It is most likely, therefore, that the low-velocity regions beneath northeast Honshu are relatively high in temperature and partial melting likely occurs in

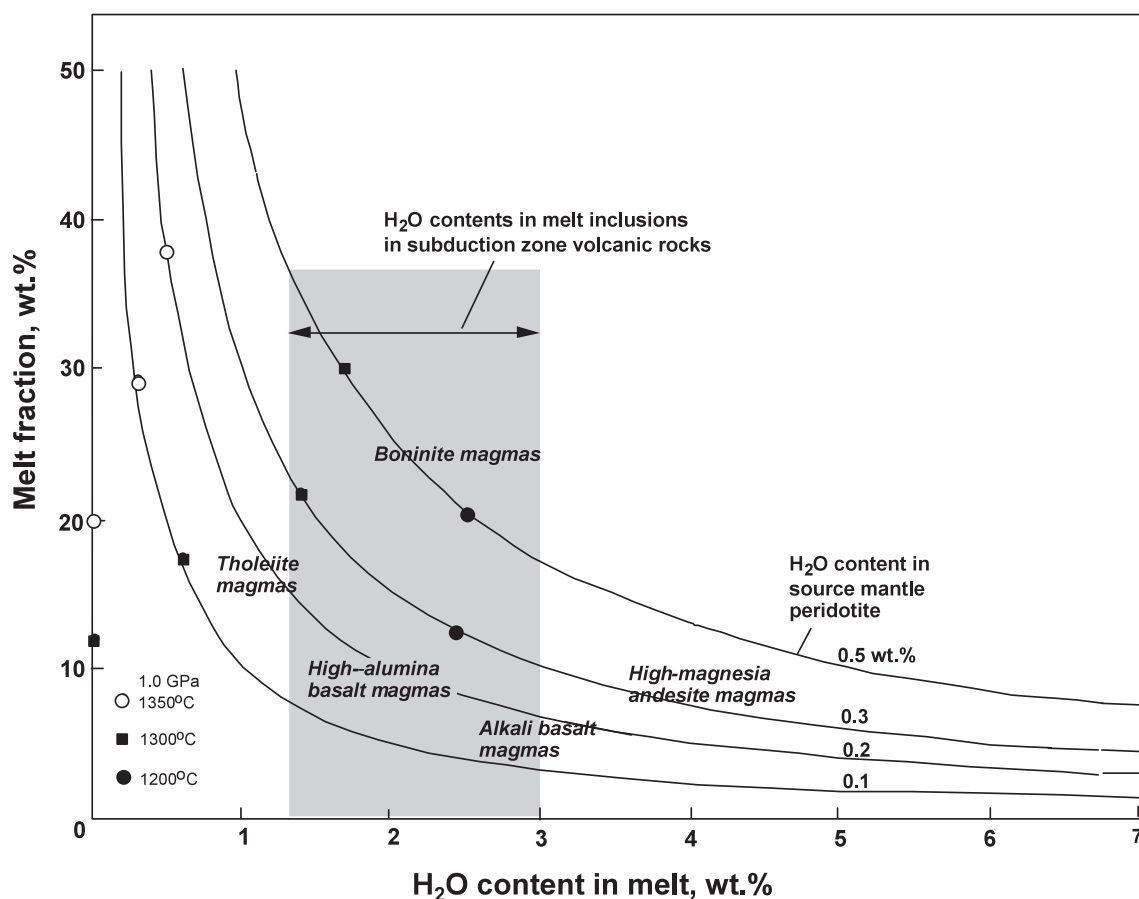


Fig. 9. Relationships between H_2O content in melts and melt fraction (degree of melting) obtained experimentally.³⁹⁾ Possible H_2O contents and melt fractions in representative primary subduction zone magmas are shown. Curves indicate relations between H_2O contents in the source mantle and those in the primary magmas, assuming that H_2O completely partitions into magmas when melting occurs. The H_2O contents in melt inclusions are from Sobolev and Chaussidon.³⁷⁾

these regions. The velocities of both P and S waves decrease with increasing degree of melting or the amount of melt generated. The relationship between elastic wave velocities and the degree of melting (melt fraction) has been determined at 1 and 0.5 GPa for a mantle peridotite.^{56), 57)} Fig. 11a shows P-wave velocity changes as function of melt fraction at 1.0 GPa, and Fig. 11b shows P- and S-wave velocity changes relative to those at the solidus temperature as function of melt fraction.⁵⁸⁾ The 3–6% negative perturbation corresponds to 2–5 vol.(volume)% melt fraction from the relationship in Fig. 11a, and to 2–6 vol.% from Fig. 11b (including uncertainties of the measurements of approximately ± 1 absolute % in the 3–5% range). Under anhydrous conditions, 2–6 vol.% (2–5 wt.%) melts are formed at 1320–1360 °C at 1.5 GPa by partial melting of a depleted peridotite (MORB source peridotite) using the calculations of

Gaetani and Grove.⁴¹⁾ In the presence of H_2O , temperature for producing the same amount of melt lowers significantly as mentioned before; for example, in the presence of 0.15 wt.% H_2O , 2–5 wt.% melts are formed from the same depleted peridotite at 1190–1300 °C at 1.5 GPa. The amount of H_2O present in the mantle beneath the Japanese island arc and other subduction zones is not known. However, based on the H_2O contents in melt inclusions in olivine in primitive island arc magmas and the extents of melting estimated above (Fig. 9), the H_2O contents in the source mantle would range from 0.1–0.2 wt.% for tholeiite and high-alumina basalt (and probably some alkali basalt) magmas, and 0.2–0.5 wt.% for boninite and high-magnesia andesite magmas. The temperatures calculated using the calculations of Gaetani and Grove with 0.15 wt.% H_2O would be reasonable estimates for Japanese island arc and

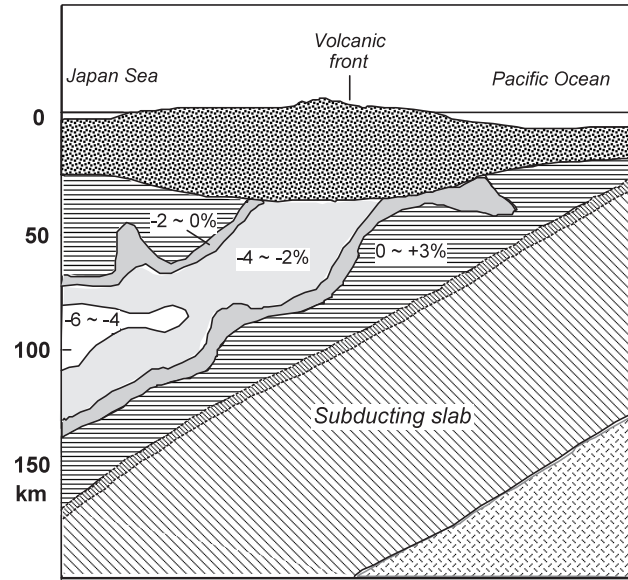


Fig. 10. Velocity perturbations of P wave (in %) in the mantle wedge of northeast Honshu between latitude 37° and 38° north.⁵⁵⁾

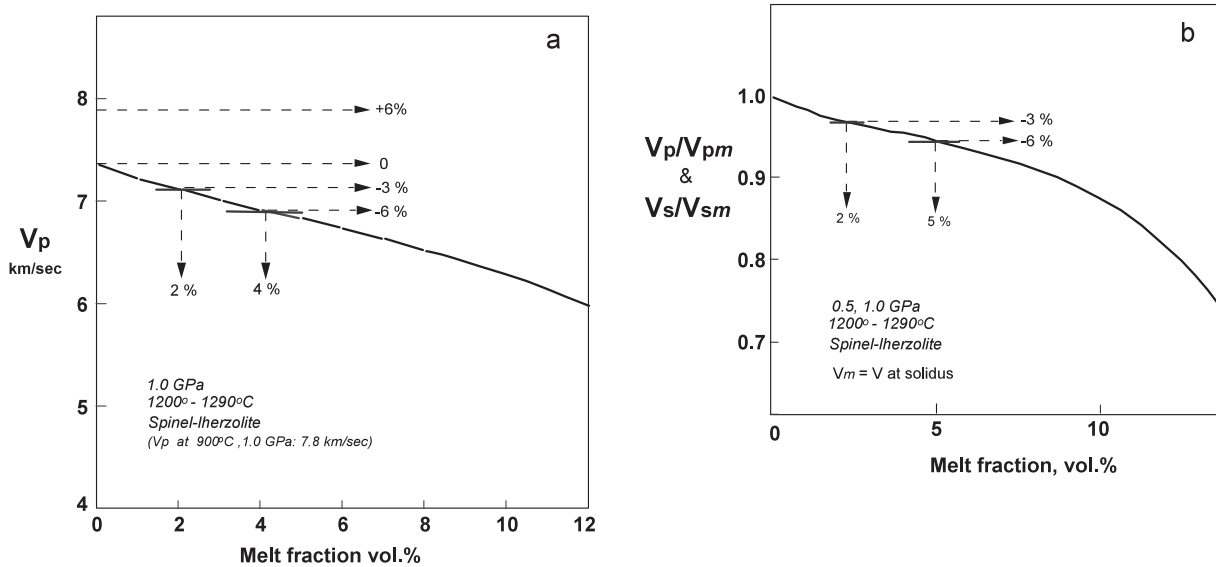


Fig. 11. Relationships between elastic wave velocities and melt fraction (degree of melting) of mantle peridotite (spinel-lherzolite) at 1.0 and 0.5 GPa.^{56)–58)} a: V_p ; b: V_p/V_{pm} and V_s/V_{sm} relative to those at the solidus temperature (V_p/V_{pm} and V_s/V_{sm} , respectively). Both of them are nearly identical.

many other subduction zones, except for the areas where boninite and high-magnesian andesites dominate.

As discussed above, primary tholeiite and high-alumina basalt magmas are generated by as much as 15 and 25 wt.% melting of mantle peridotite sim-

ilar to relatively fertile peridotites PHN1611 and KLB1. Therefore, if the mantle wedge of northeast Honshu consists of such relatively fertile peridotites, primary tholeiite and high-alumina basalt magmas cannot be formed with the velocity structures of Fig. 10 in which 2–5 wt.% melting likely oc-

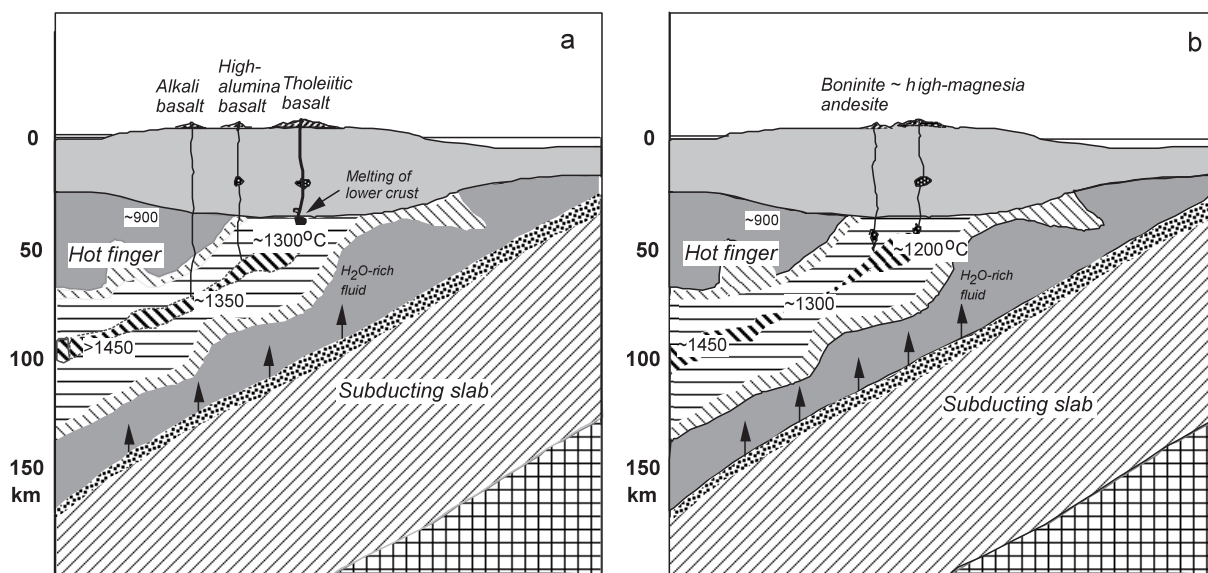


Fig. 12. Possible temperature distributions in the hot fingers with two different H_2O contents to generate subduction zone magmas. a: H_2O content 0.1~0.2 wt.%; b: 0.2~0.5 wt.%.

curs. If the mantle wedge of northeast Honshu consists of more depleted peridotites, those magmas may be formed with the velocity structures of Fig. 10. To resolve this problem, seismic velocity structures with higher precisions are needed. In any case, primary tholeiite and high-alumina basalt magmas would be formed in higher temperature parts of the mantle, and such higher-temperature parts (blocks) of the mantle would ascend from deeper parts of the mantle wedge intermittently. Tamura *et al.*⁵⁹⁾ recognized that Quaternary volcanoes in northeast Honshu form 10 clusters separated by 20–50 km spaces, and that each cluster extends along an east-west direction. Beneath the volcano clusters, seismic low-velocity regions exist, which Tamura *et al.*⁵⁹⁾ called 'hot fingers'. Fig. 10 is the seismic velocity structure of one hot finger. The high-temperature blocks of the mantle or diapirs, in which primary tholeiite and high-alumina basalt magmas are generated, may ascend within the hot fingers or ascend nearly vertically from the mantle below the hot fingers. In the former case, hot blocks ascend obliquely from the deeper part of the hot fingers on the Japan Sea side toward the shallower part on the Pacific Ocean side within or along the hot fingers and generate magmas. Fig. 12 shows possible temperature distributions in the hot fingers with two different H_2O contents to generate representative subduction zone magmas. Fig. 12a and b are for H_2O contents

0.1~0.2 wt.% and 0.2~0.5 wt.%, respectively. In the former case, tholeiitic basalt, high-alumina basalt and alkali basalt magmas are formed, whereas in the latter case, boninite and high-magnesia andesite magmas are formed.

Density of basalt magmas in relation to their ascent rates

Most primary basalt magmas formed in the mantle fractionate or crystallize to varying degrees during their ascent toward the surface. In the Japanese island arc, tholeiite magmas tend to fractionate more extensively than alkali basalt magmas, as inferred from their $\text{Mg}/(\text{Mg}+\text{Fe})$ ratios.⁶⁰⁾ This is supported by the fact that many alkali basalts carry xenoliths of mantle peridotite, whereas tholeiites never carry them. Magmas carrying heavy mantle xenoliths must ascend rapidly from the mantle to the surface without significant crystal settling or crystal fractionation. A possible factor controlling the rate of magma ascent could be the density of magma. The densities of tholeiitic and alkali basaltic melts were measured at high pressures using 'falling and floating sphere method'.⁶¹⁾ Fig. 13 shows the results of density measurements of anhydrous melts of two different primary tholeiite compositions and two different primary alkali basalt compositions. As shown in the figure, melts of the primary tholeiite compositions are denser than those of the primary al-

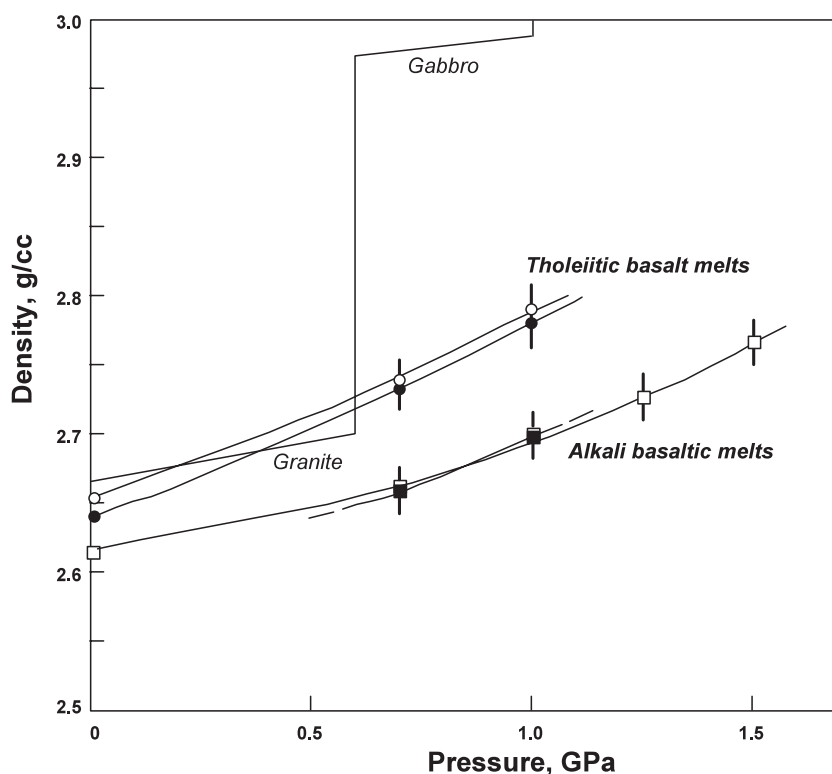


Fig. 13. Melt densities of tholeiitic basalt and alkali basalt.⁶⁰⁾ A simplified density profile in northwest Honshu is also shown.

alkali basalt compositions by $0.07\text{--}0.08\text{ g/cm}^3$ at pressure between 0.5 and 1.0 GPa. The density difference between the melts of primary tholeiite compositions and those of primary alkali basalt compositions would be mostly due to the difference in the contents of alkalis which effectively reduce the density of melts; the $\text{Na}_2\text{O}+\text{K}_2\text{O}$ contents are 1.78 and 1.84 wt.% $\text{Na}_2\text{O}+\text{K}_2\text{O}$ in the former melts, and 4.46 and 5.44 wt.% in the latter melts. Alkali basalts erupted near the Japan Sea often contain amphibole, indicating that the alkali basalt magmas would contain significant amounts of H_2O and other volatile components such as CO_2 and F, which further reduce the density of magma. On the other hand, most tholeiite magmas contain smaller amounts of H_2O and other volatile components. The density difference between actual alkali basalt and tholeiite magmas would, therefore, be greater than that shown in the measurements made under anhydrous, volatile-free conditions. The same figure shows a simplified density profile of the crust in northeast Honshu that consists of an upper granitic layer and a lower gabbroic layer. It is shown that the den-

sities of primary alkali basalt melts are less than those of granite and gabbro, whereas the densities of primary tholeiite melts are less than that of gabbro but partly larger than that of granite. It means that primary alkali basalt magmas can ascend continuously through both gabbroic and granitic layers, but primary tholeiite magmas cannot ascend through granitic layers and instead would fractionate or crystallize at the base of the granitic layer before ascending to the surface. This argument is, however, based on a very simplified crustal model and on density measurements of a limited number of basaltic melts. It should therefore be tested by further density measurements of melts, particularly melts of alkali basalt compositions with volatile components, and by considering density profiles more like those of the actual crust.

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Profile

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